

Search for CP violation in  $D^0 \rightarrow h^+ h^-$  decays at CDF

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I report on a measurement of  $CP$ -violating asymmetries ( $A_\Gamma$ ) between effective lifetimes of  $D^0$  or  $\bar{D}^0$  in fully reconstructed  $D^0 \rightarrow K^+ K^-$  and  $D^0 \rightarrow \pi^+ \pi^-$  decays collected in  $p\bar{p}$  collisions by the Collider Detector at Fermilab experiment. The full CDF data set corresponding to  $9.7 \text{ fb}^{-1}$  of integrated luminosity is used. The flavor of the charm meson at production is determined by exploiting the strong-interaction decay  $D^{*+} \rightarrow D^0 \pi^+$ , while the contamination from mesons originated in  $b$ -hadron decays is evaluated and subtracted from the sample. Signal yields as functions of the observed decay-time distributions are extracted from maximum likelihood fits and used to measure the asymmetries. The results,  $A_\Gamma(K^+ K^-) = (-1.9 \pm 1.5 \text{ (stat)} \pm 0.4 \text{ (syst)}) \times 10^{-3}$  and  $A_\Gamma(\pi^+ \pi^-) = (-0.1 \pm 1.8 \text{ (stat)} \pm 0.3 \text{ (syst)}) \times 10^{-3}$ , and their combination,  $A_\Gamma = (-1.2 \pm 1.2) \times 10^{-3}$ , are consistent with the SM predictions and other experimental determinations.

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# 1 Introduction

In charm transitions, the standard model (SM) predicts  $CP$ -violating effects not exceeding  $O(10^{-2})$  [1]. Indeed, no  $CP$ -violating effects have been firmly established yet in charm dynamics [2].

The decay-time-dependent rate asymmetries of charm mesons two body hadron decays ( $D \rightarrow h^+h^-$ ,  $h = K, \pi$ ),

$$\mathcal{A}_{CP}(t) = \frac{d\Gamma(D^0 \rightarrow h^+h^-)/dt - d\Gamma(\bar{D}^0 \rightarrow h^+h^-)/dt}{d\Gamma(D^0 \rightarrow h^+h^-)/dt + d\Gamma(\bar{D}^0 \rightarrow h^+h^-)/dt}, \quad (1)$$

probe non-SM physics contributions in the *oscillation* and *penguin* transition amplitudes which could be affected by non-SM contributions that enhance the magnitude of the observed  $CP$  violation w.r.t. SM expectation. The asymmetry  $\mathcal{A}_{CP}(t)$  includes both direct and indirect  $CP$  violation effects. The slow oscillations rate [2] of charm mesons allows approximating Eq. (1) as [3],

$$\mathcal{A}_{CP}(t) \approx \mathcal{A}_{CP}^{\text{dir}}(h^+h^-) - \frac{\langle t \rangle}{\tau} A_{\Gamma}(h^+h^-) \text{ with } A_{\Gamma} = \frac{\hat{\tau}(\bar{D}^0 \rightarrow h^+h^-) - \hat{\tau}(D^0 \rightarrow h^+h^-)}{\hat{\tau}(\bar{D}^0 \rightarrow h^+h^-) + \hat{\tau}(D^0 \rightarrow h^+h^-)} \quad (2)$$

where  $\langle t \rangle$  is the sample mean of decay time,  $\tau$  is the  $CP$ -averaged  $D$  lifetime [2],  $\mathcal{A}_{CP}^{\text{dir}}$  is related to direct  $CP$  violation, and  $A_{\Gamma}$  is the asymmetry between the *effective* lifetimes  $\hat{\tau}$  of  $D^0$  and  $\bar{D}^0$  and is mostly due to indirect  $CP$  violation. Recent measurements of  $A_{\Gamma}$  [4] showed consistency with  $CP$  symmetry with  $O(10^{-3})$  uncertainties. However, additional determinations with comparable precision may improve the knowledge of  $CP$  violation in the charm sector. In this note I report a measurement of  $A_{\Gamma}$  using fully reconstructed  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  decays collected in  $p\bar{p}$  collisions by the Collider Detector at Fermilab experiment. The full CDF data set corresponding to  $9.7 \text{ fb}^{-1}$  of integrated luminosity is used.

## 2 Selection and reconstruction

Online data selection is based on pairs of charged particles displaced from the  $p\bar{p}$  collision point. Offline, a  $D$  candidate is reconstructed using two oppositely charged tracks fit to a common decay vertex. A charged particle with  $p_T > 400 \text{ MeV}/c$  is associated with each  $D$  candidate to form  $D^{*\pm}$  candidates. Constraining the  $D^{*\pm}$  decay vertex to lie on the beam-line results in a 25% improvement in  $D^{*\pm}$  mass resolution w.r.t Ref. [3]. Ref. [3] details the offline selection. The  $h^+h^-$  mass of selected candidates is required to be within about  $24 \text{ MeV}/c^2$  of the known  $D^0$  mass,  $m_{D^0}$  [2], to separate  $D \rightarrow K^+K^-$  and  $D \rightarrow \pi^+\pi^-$  samples. Final selected samples contain  $6.1 \times 10^5$   $D^0 \rightarrow K^+K^-$ ,  $6.3 \times 10^5$   $\bar{D}^0 \rightarrow K^+K^-$ ,  $2.9 \times 10^5$   $D^0 \rightarrow \pi^+\pi^-$ ,

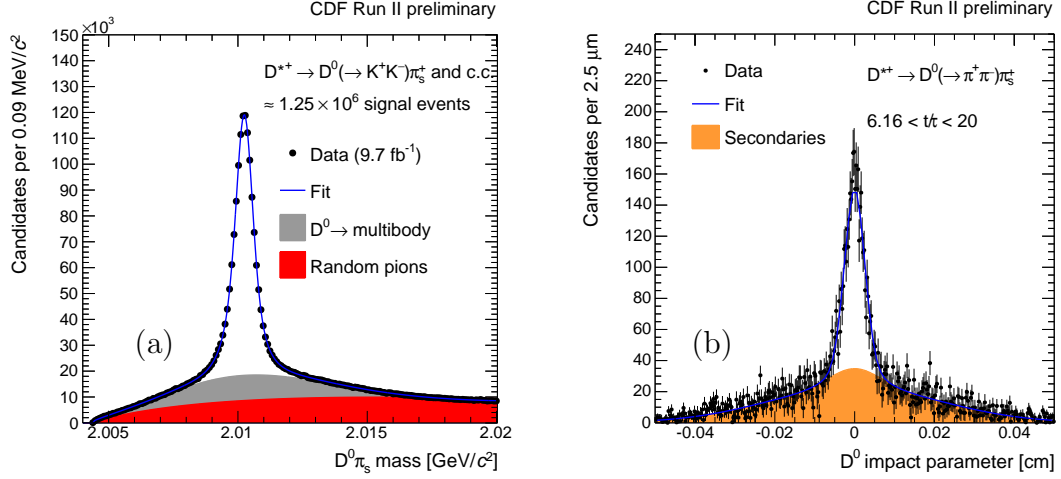


Figure 1: Distributions of  $D\pi^\pm$  mass with fit results overlaid for the  $D \rightarrow K^+K^-$  sample (a). Distributions of  $D^0$  impact parameter with fit results overlaid for background-subtracted  $D^{*+} \rightarrow D^0(\rightarrow \pi^+\pi^-)\pi_s^+$  decays restricted to the decay-time bin  $6.16 < t/\tau < 20$  (b).

and  $3.0 \times 10^5$   $\bar{D}^0 \rightarrow \pi^+\pi^-$  signal events. The main backgrounds are real  $D^0$  decays associated with random pions or random combinations of three tracks (combinatorics) for the  $\pi^+\pi^-$  sample, while the  $K^+K^-$  sample is also polluted by misreconstructed multibody charm meson decays (i.e.  $D^0 \rightarrow h^-\pi^+\pi^0$  and  $D^0 \rightarrow h^-\ell^+\nu_\ell$ , where  $\ell$  is a muon or an electron), Figure. 1.

### 3 Determination of the asymmetry

The flavor-conserving strong-interaction processes  $D^{*+} \rightarrow D^0\pi^+$  and  $D^{*-} \rightarrow \bar{D}^0\pi^-$  allow identification of the initial flavor through the charge of the low-momentum  $\pi$  meson (soft pion,  $\pi_s$ ).  $D^0$  or  $\bar{D}^0$  subsamples are thus divided in equally populated 30 bins of decay time between  $0.15\tau$  and  $20\tau$ . In each bin, the average decay-time  $\langle t \rangle$  is determined from a sample of about  $13 \times 10^6$   $D^{*\pm} \rightarrow D(\rightarrow K^\mp\pi^\pm)\pi_s^\pm$  signal decays. Signal and background yields in the signal region are determined in each decay-time bin, and for each flavor, through  $\chi^2$  fits of the  $D\pi_s^\pm$  mass distribution. The functional form of the signal shapes is determined from simulation [3], with parameters tuned in the sample of  $D \rightarrow K^\mp\pi^\pm$  decays, independently for each  $D$  flavor and decay-time bin. The resulting signal-to-background proportions are used to construct signal-only distributions of the  $D$  impact parameter (IP). In each bin and for each flavor background-subtracted IP distributions are formed by subtracting IP distributions of background candidates, sampled in the  $2.015 < M(D\pi^\pm) < 2.020$  GeV/ $c^2$

region for the  $\pi^+\pi^-$  sample, from IP distributions of signal candidates which have  $M(D\pi_s^\pm)$  within  $2.4 \text{ MeV}/c^2$  of the known  $D^{*\pm}$  mass [2]. Contamination from multi-body decays in the  $K^+K^-$  sample is taken into account using as background candidates in the sideband  $m_{D^0} - 64 \text{ MeV}/c^2 < M(K^+K^-) < m_{D^0} - 40 \text{ MeV}/c^2$  and with  $M(D\pi_s^\pm)$  within  $2.4 \text{ MeV}/c^2$  of the known  $D^{*\pm}$  mass. A  $\chi^2$  fit of these signal-only IP distributions identifies  $D^{*\pm}$  mesons from  $b$ -hadron decays (*secondary*) and determines the yields of charm ( $N_{D^0}$ ) and anticharm ( $N_{\bar{D}^0}$ ) mesons directly produced in the  $p\bar{p}$  collision (*primary*). Double-Gaussian models are used for both the primary and secondary components. The parameters of the primary component are derived from a fit of candidates in the first decay-time bin ( $t/\tau < 1.18$ ), where any bias from the  $\mathcal{O}(\%)$  secondary contamination is negligible, and fixed in all fits. The parameters of the secondary component are determined by the fit independently for each decay-time bin, Figure 1. The yields are then combined into the asymmetry  $A = (N_{D^0} - N_{\bar{D}^0})/(N_{D^0} + N_{\bar{D}^0})$ , which is fit with the linear function in Eq. (2). The slope of the function, which yields  $A_\Gamma$ , is extracted using a  $\chi^2$  fit. The fit is shown in Fig. 2 and yields  $A_\Gamma(K^+K^-) = (-1.9 \pm 1.5 \text{ (stat)}) \times 10^{-3}$  and  $A_\Gamma(\pi^+\pi^-) = (-0.1 \pm 1.8 \text{ (stat)}) \times 10^{-3}$ . In both samples, we observe a few percent value for  $A(0)$ , due to the known detector-induced asymmetry in the soft-pion reconstruction efficiency [3]. The independence of instrumental asymmetries from decay time is demonstrated by the analysis of  $D \rightarrow K^\mp\pi^\pm$  decays, where no indirect  $CP$  violation occurs and instrumental asymmetries are larger; an asymmetry compatible with zero is found,  $(-0.5 \pm 0.3) \times 10^{-3}$ .

For the  $\pi^+\pi^-$  analysis, the dominant systematic uncertainty of 0.028% arises from the choice of the impact-parameter shape of the secondary component whereas for the  $K^+K^-$  sample this effect only contributes 0.013%. The choice of the background sideband has a dominant effect in the  $K^+K^-$  analysis (0.038%) and a minor impact (0.010%) on the  $\pi^+\pi^-$  result.

## 4 Conclusions

A measurement of the difference in effective lifetime between anticharm and charm mesons reconstructed in  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  decays using the full CDF data set is reported. The final results,

$$\begin{aligned} A_\Gamma(\pi^+\pi^-) &= (-0.1 \pm 1.8 \text{ (stat)} \pm 0.3 \text{ (syst)}) \times 10^{-3}, \\ A_\Gamma(K^+K^-) &= (-1.9 \pm 1.5 \text{ (stat)} \pm 0.4 \text{ (syst)}) \times 10^{-3}, \end{aligned} \quad (3)$$

are consistent with  $CP$  symmetry and combined to yield  $A_\Gamma = (-1.2 \pm 1.2) \times 10^{-3}$  [5]. The results are also consistent with the current best results [4], have the second best precisions, and contribute to improve the global constraints on indirect  $CP$  violation in charm meson dynamics.

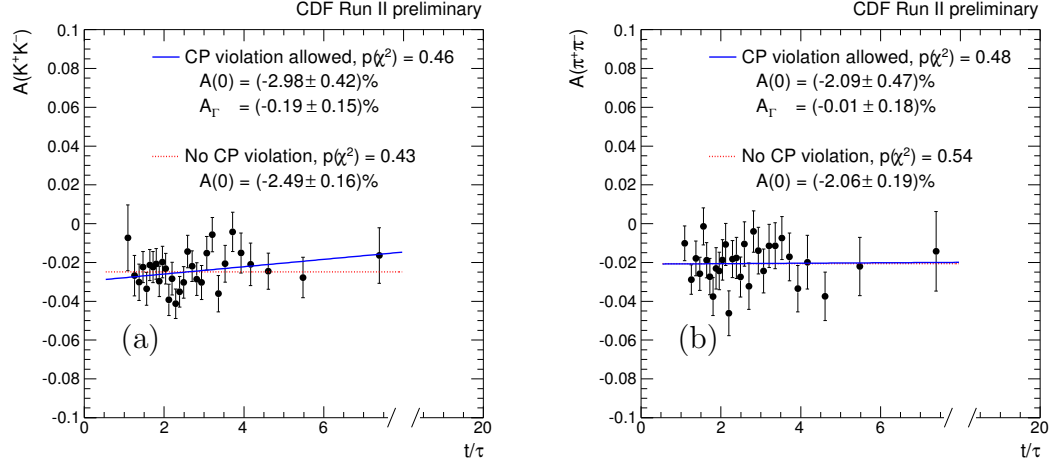


Figure 2: Effective lifetime asymmetries as functions of decay time for the (a)  $D \rightarrow K^+K^-$  and (b)  $D \rightarrow \pi^+\pi^-$  samples. Results of fits not allowing for (red dotted line) and allowing for (blue solid line)  $CP$  violation are overlaid.

## References

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